Precision synchronization over large Doppler ranges for satellite-based free-space quantum networking

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SPIE Quantum West

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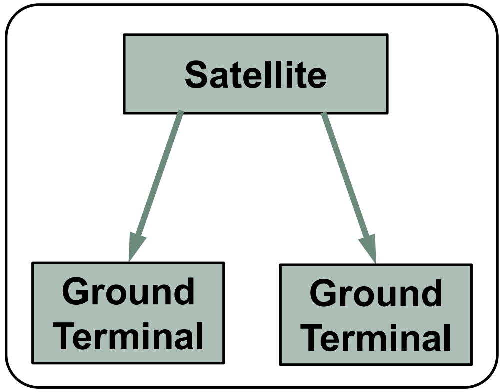
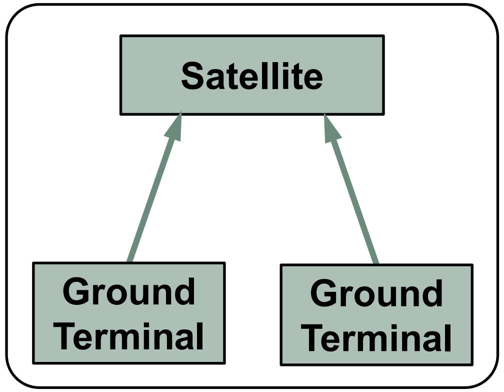
Quantum Network Link Topologies

Dual Downlink



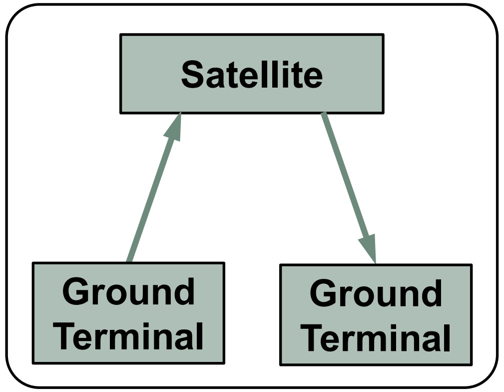
- Entanglement source on satellite
- Photonic qubits sent to different ground stations
- Space-ground synchronization is independent for each downlink

Dual Uplink



- Entanglement sources at both ground stations send qubits to satellite
- Optical Bell state measurement on satellite entangles remaining qubits at ground stations
- Both uplinked qubits must be synchronized at satellite

Uplink / Downlink



- Entanglement source at one ground station
- Photonic qubit sent via satellite-based passive relay to second ground station
- No space-ground synchronization required

Synchronization techniques are critical to realizing efficient high-rate entanglement distribution

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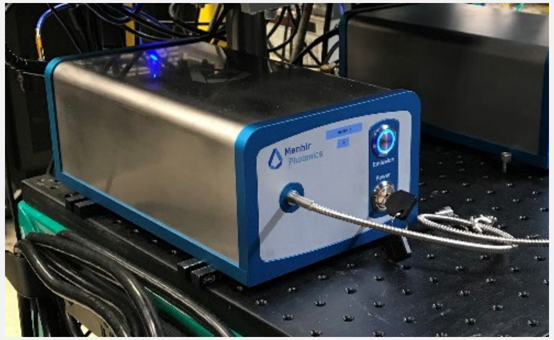
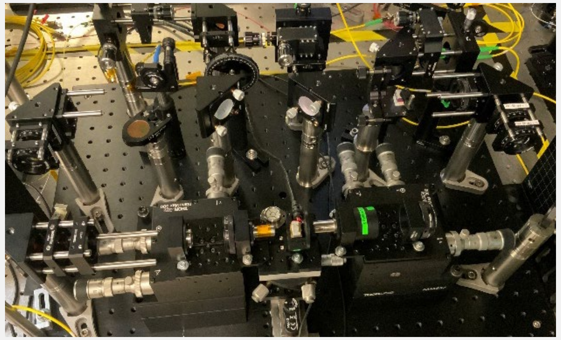
Entangled Photon Sources

Pump Mode-Locked Laser



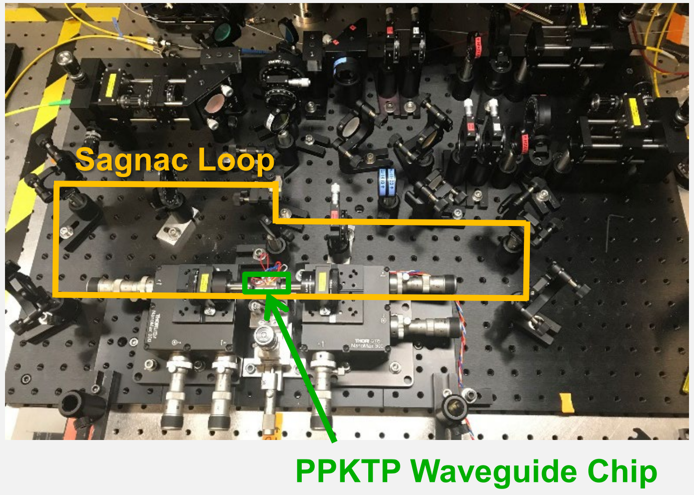
1550 nm center wavelength
1 GHz repetition rate

Pump Wavelength Converter



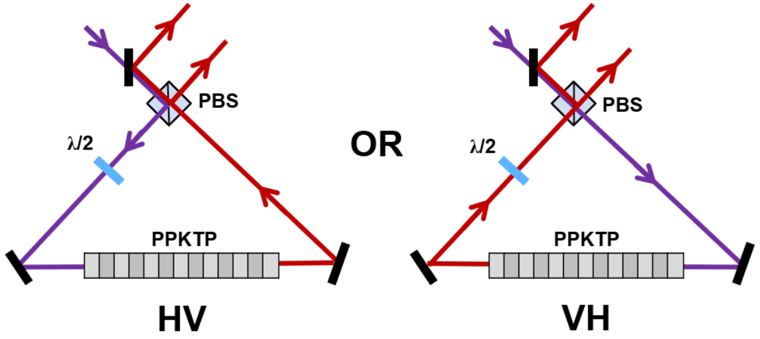
Second harmonic generation (SHG)
1550 → 775 nm

Entanglement Setup (SPDC)



- Entanglement sources generate pairs at high rate with high fidelity using tunable mode-locked laser sources well suited to the quantum networking architecture
- Short pulse duration presents challenging synchronization requirements

- 1 GHz system clock rate
- ~1 ps pulse duration
- ~0.01 average pairs / pulse
- 0.963 entangled state fidelity
  - Measure of "closeness" of two quantum states



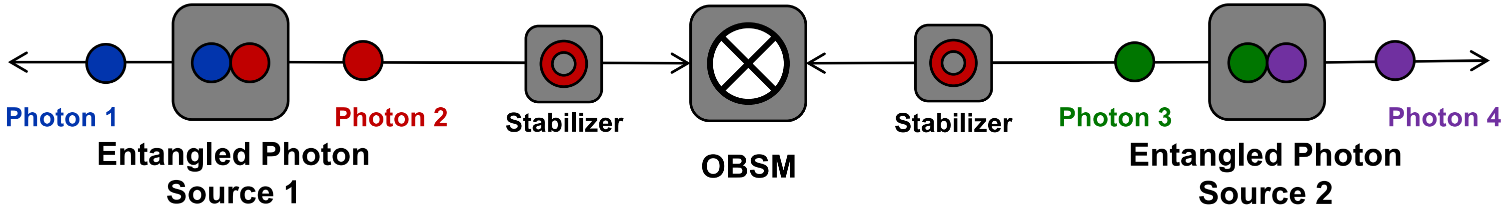
$$|\Psi^-\rangle \propto |HV\rangle - |VH\rangle$$

SPDC: Spontaneous Parametric Down Conversion
PPTKP: Periodically Poled $KTiPO_4$

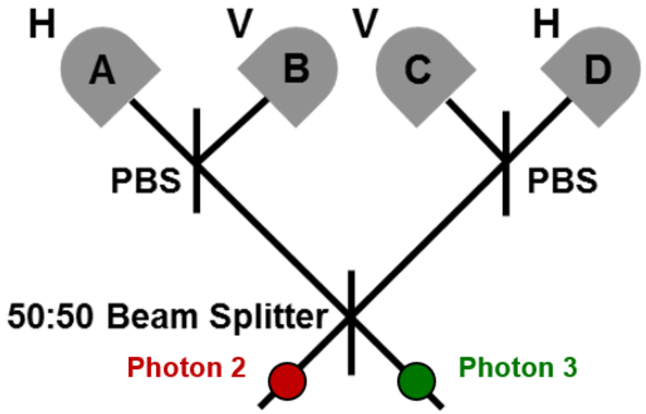
H: Horizontal Polarization
V: Vertical Polarization
PBS: Polarizing Beam Splitter

Entanglement Swap and Temporal Overlap at OBSM

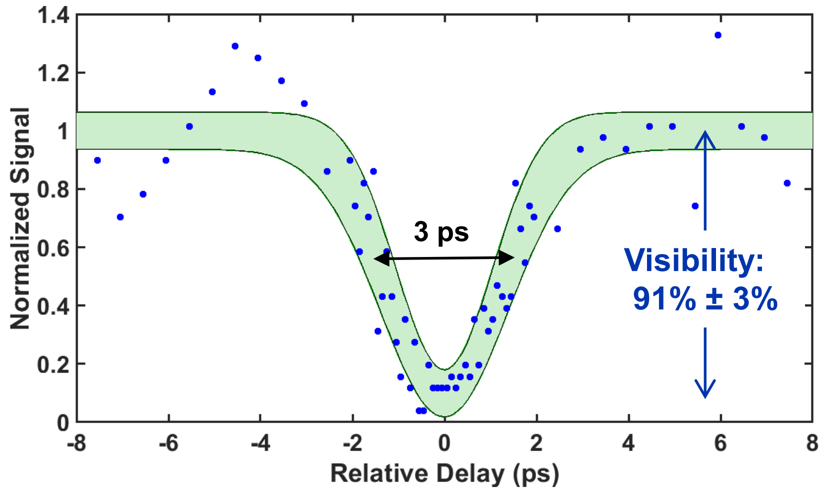
- **OBSM swaps entanglement to remote photons 1 and 4**
- **Photons 2 and 3 need to temporally overlap at OBSM**
  - **Overlap precision set by photon temporal duration**
- **Hong-Ou-Mandel (HOM) interference 'dip' exhibits photon temporal overlap**
  - **Places upper bound on entanglement swap fidelity**
  - **Characterizes photon synchronization**



Optical Bell State Measurement (OBSM)



HOM Interference Dip



High-fidelity, high-rate entanglement swap with SPDC sources demands 1-ps-class synchronization

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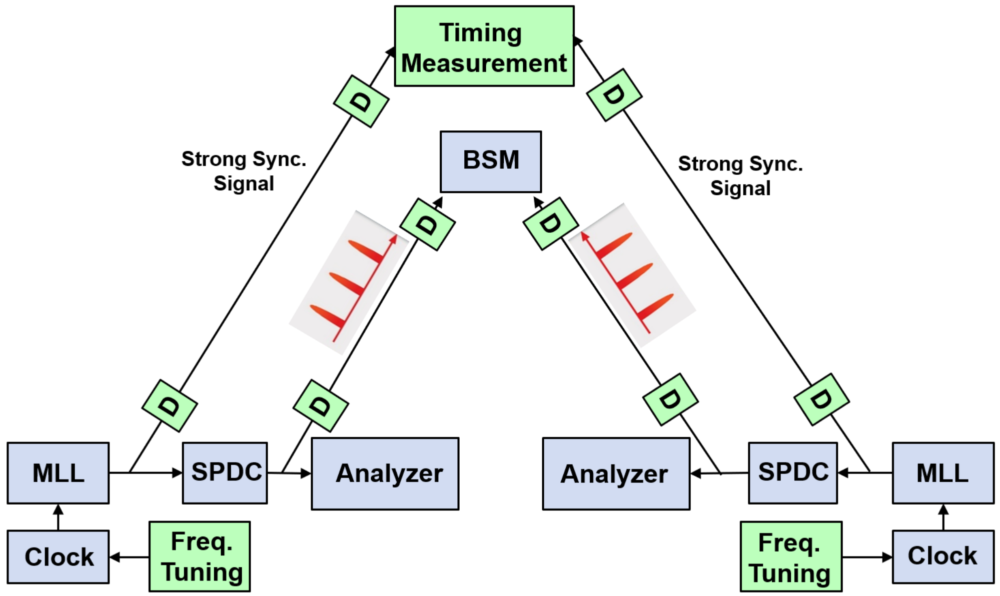
Synchronization Architecture and Analysis



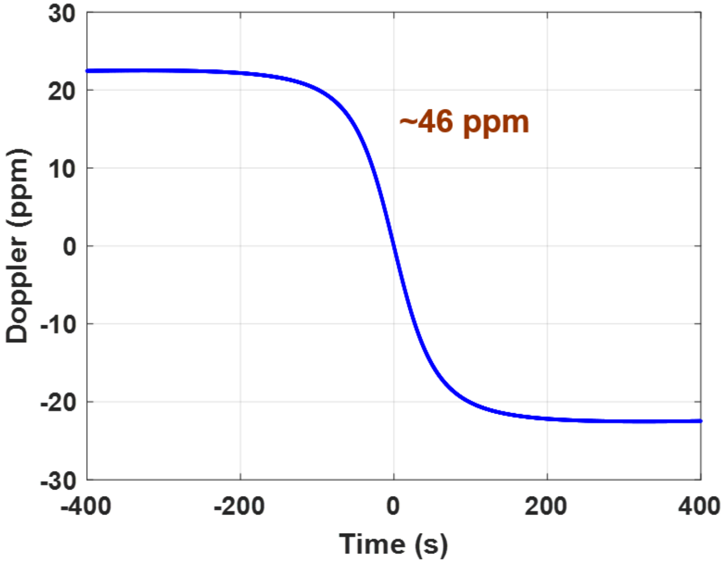
- **Proposed synchronization control technique:**
  - **Provide additional 'classical' timing signal**
  - **Relative timing measurement at space terminal via HOM dip (precise and doesn't add hardware)**
  - **Feed HOM coincidence count information to mode-locked-laser (MLL) frequency tuning control loop on ground**
- **Analysis considerations**
  - **Orbital motion (Doppler, Doppler rate-of-change, round-trip time)**
  - **Signal-to-noise ratio and tracking loop bandwidth**
  - **Doppler pre-compensation**
  - **Atmospheric effects**
  - **Source and spacecraft jitter**

High-level analysis examined performance drivers to determine viability of proposed technique

SPIE Quantum West, paper 12446, March 2023
Optica Quantum 2.0, paper QW3A.5, June 2023

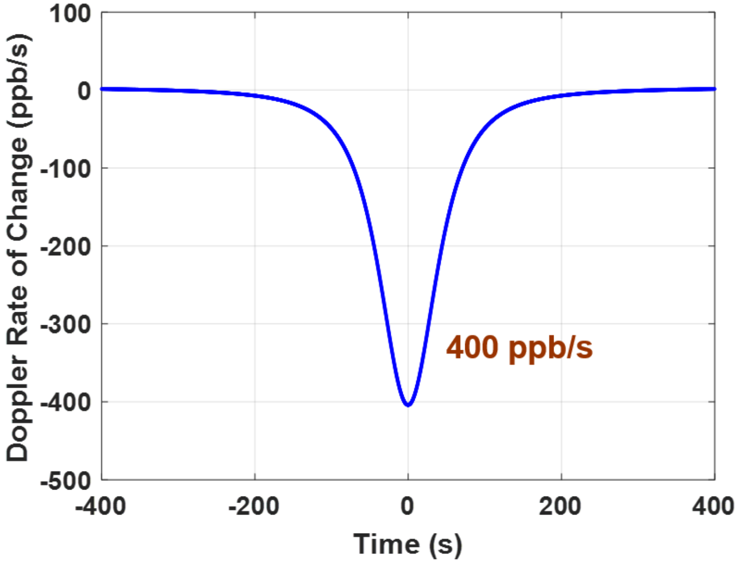
Orbital Motion

Doppler



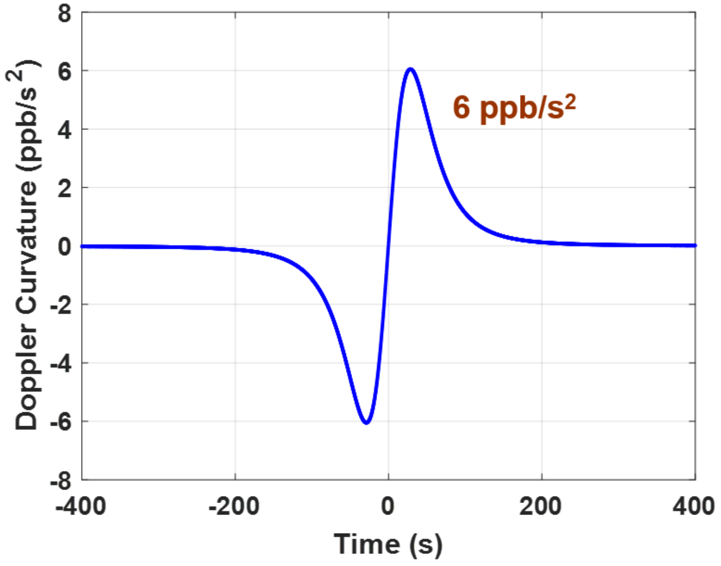
- *Doppler sets control loop throw requirement*

Doppler Rate of Change



- *Doppler rate of change sets loop bandwidth requirement*

Doppler Curvature

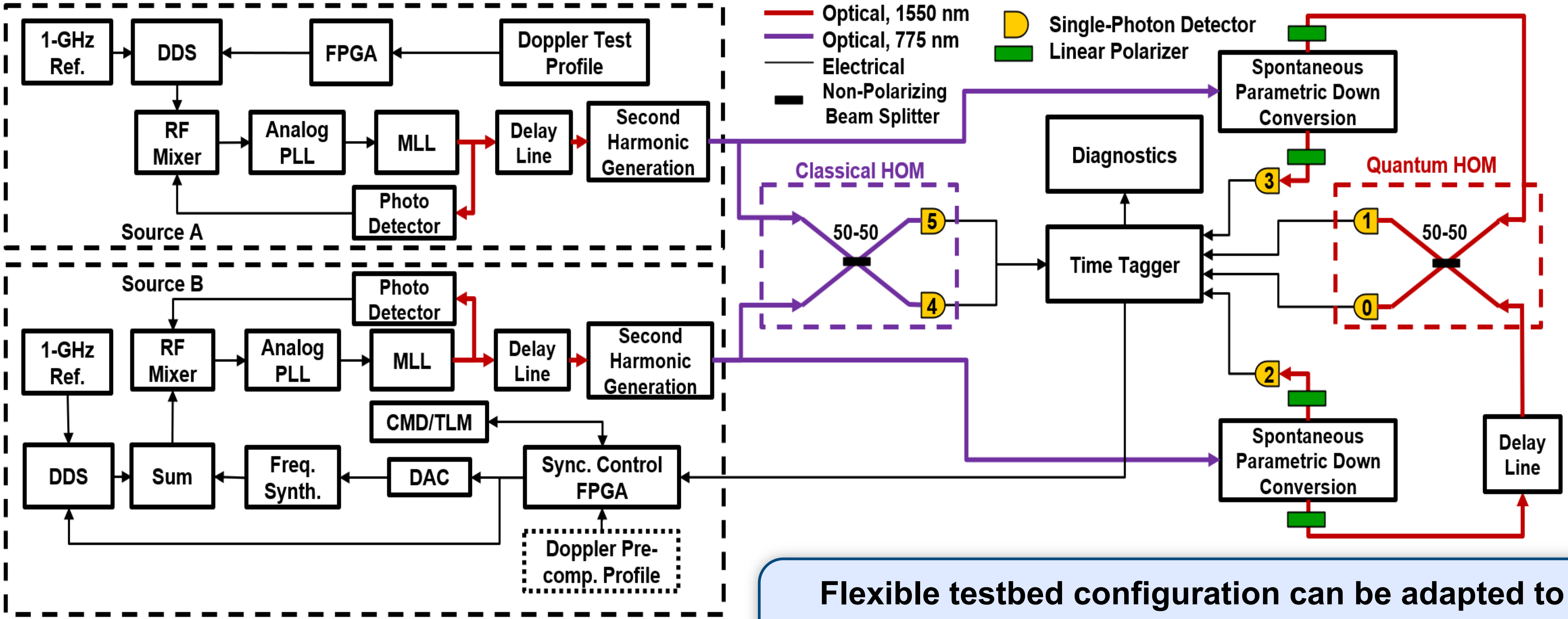


- *Curvature sets control loop residual error*

400 km Low Earth Orbit
7.7 km/s Orbital Speed
~1.3-9 ms Propagation Delay

Link architecture & satellite motion puts fundamental constraints on synchronization methods

Testbed Configuration



Flexible testbed configuration can be adapted to specific test situation and evolve as synchronization control loop matures

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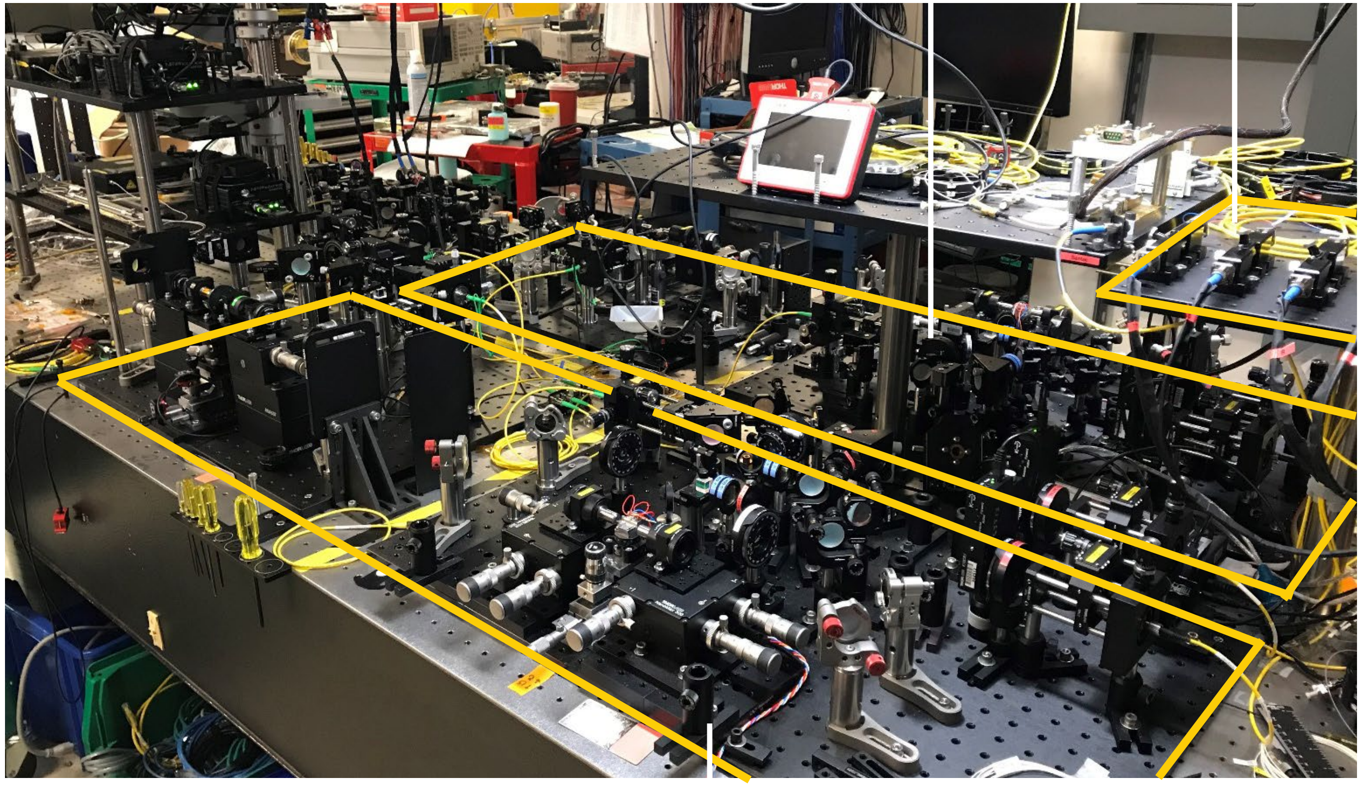
Space-Ground Entanglement Distribution Test Bed

Entangled Photon Source Pump Subsystems
(off photo)

Entangled Photon Source 1

OBSM

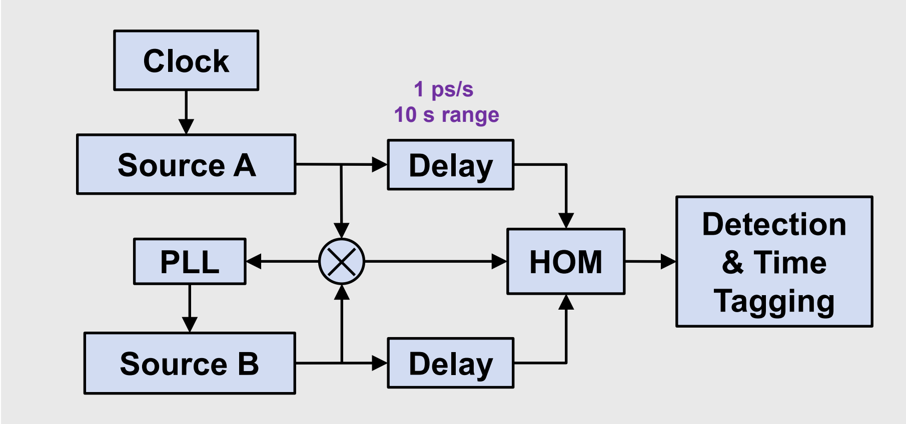


Entangled Photon Source 2

- **Two Entangled Photon Sources**
- **Optical Bell State Measurement (OBSM) with fiber connections to single-photon detectors**
- **Fiber connections to free-space link across Hanscom AFB**
- **Rolling integration test approach**
  - **Table-top testing**
  - **Free-space link testing**

HOM Measurement via Time-Tagger and Real-time FPGA Coincidence Processing

Measurement Configuration

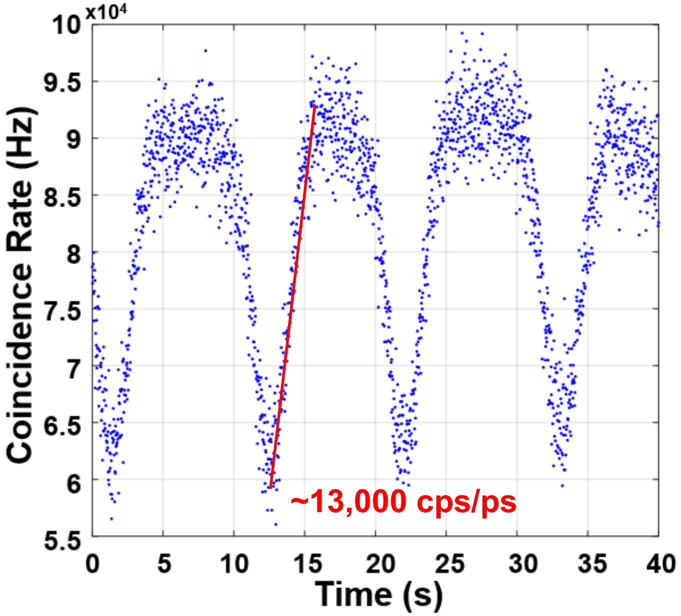


- **Measurements**
  - HOM shape and count rates
  - Confirmation of source temporal stability
  - Estimation of control loop SNR

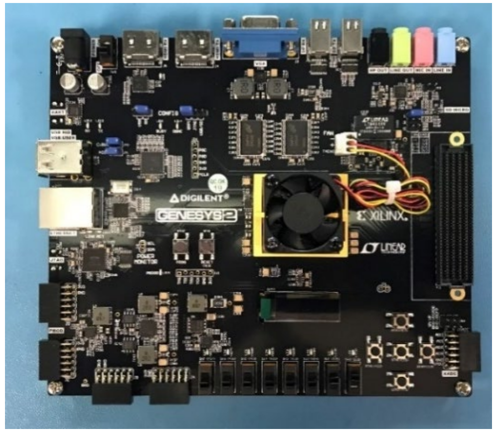
Results show precision time delay measurement capability provided by HOM interference

High-Speed Time Tagger

HOM Coincidence Scan



Real-time FPGA Control



- ~13,000 cps/ps HOM slope
- For 100 Hz (10 ms) integration time at operating point (75,000 cps), expect 750 counts and ~27 count uncertainty
  - For 130 counts/(10 ms-ps) slope, this means 27/130~0.2 ps expected timing uncertainty

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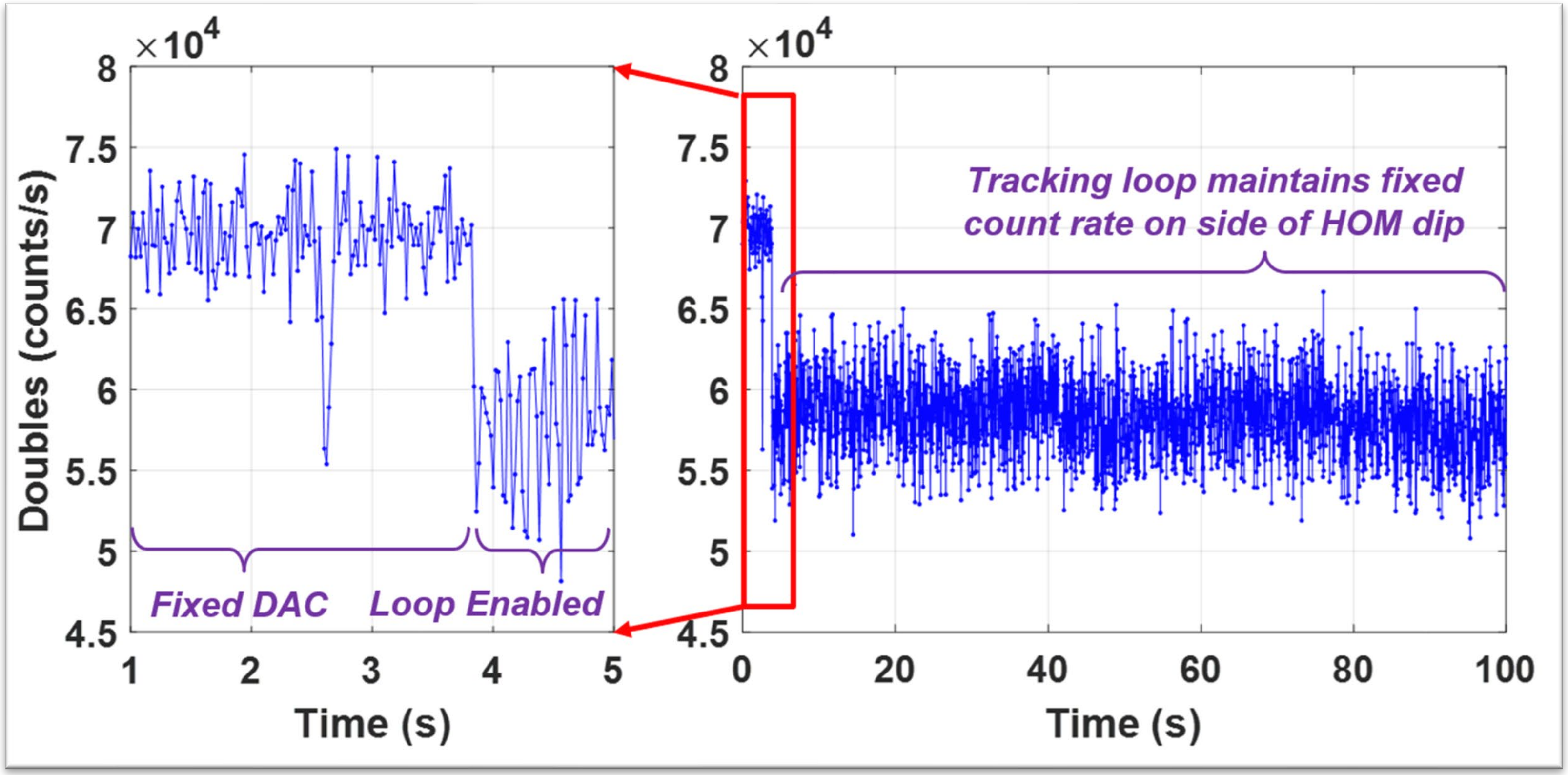
Demonstrating Synchronization



- **Simple control algorithm used coincidence-count linear feedback to adjust DAC to phase align the tracking source to the primary source**
  - **Type 1 control loop**
- **Subsequent work done to extend loop capability**
  - **Type-2: null out a frequency offset**
  - **Type-3: null out a frequency rate of change**

First demonstration of locking is important first step that validates many aspects of the method (e.g. SNR)

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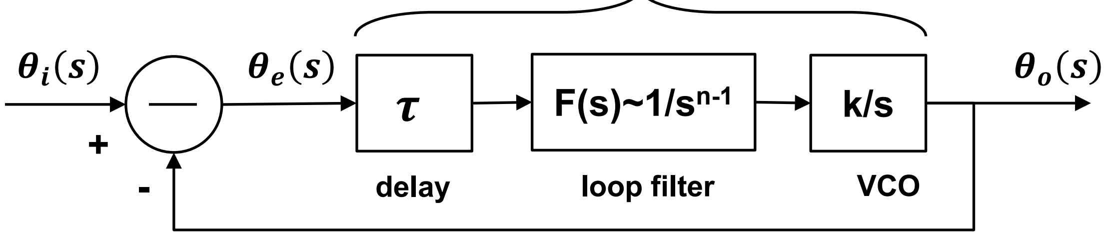
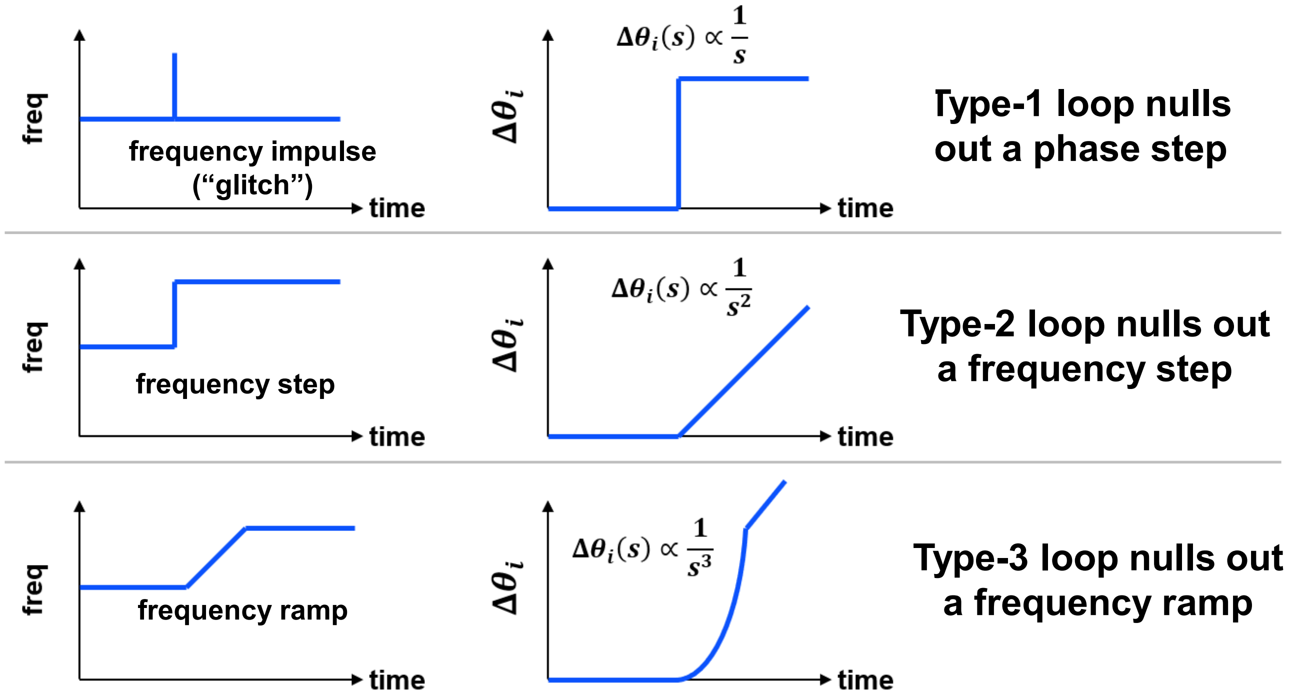
Phase-Locked Loop (PLL) Overview

$$G(s) = \frac{\theta_o(s)}{\theta_e(s)} = \frac{e^{-\tau s} k F(s)}{s}$$



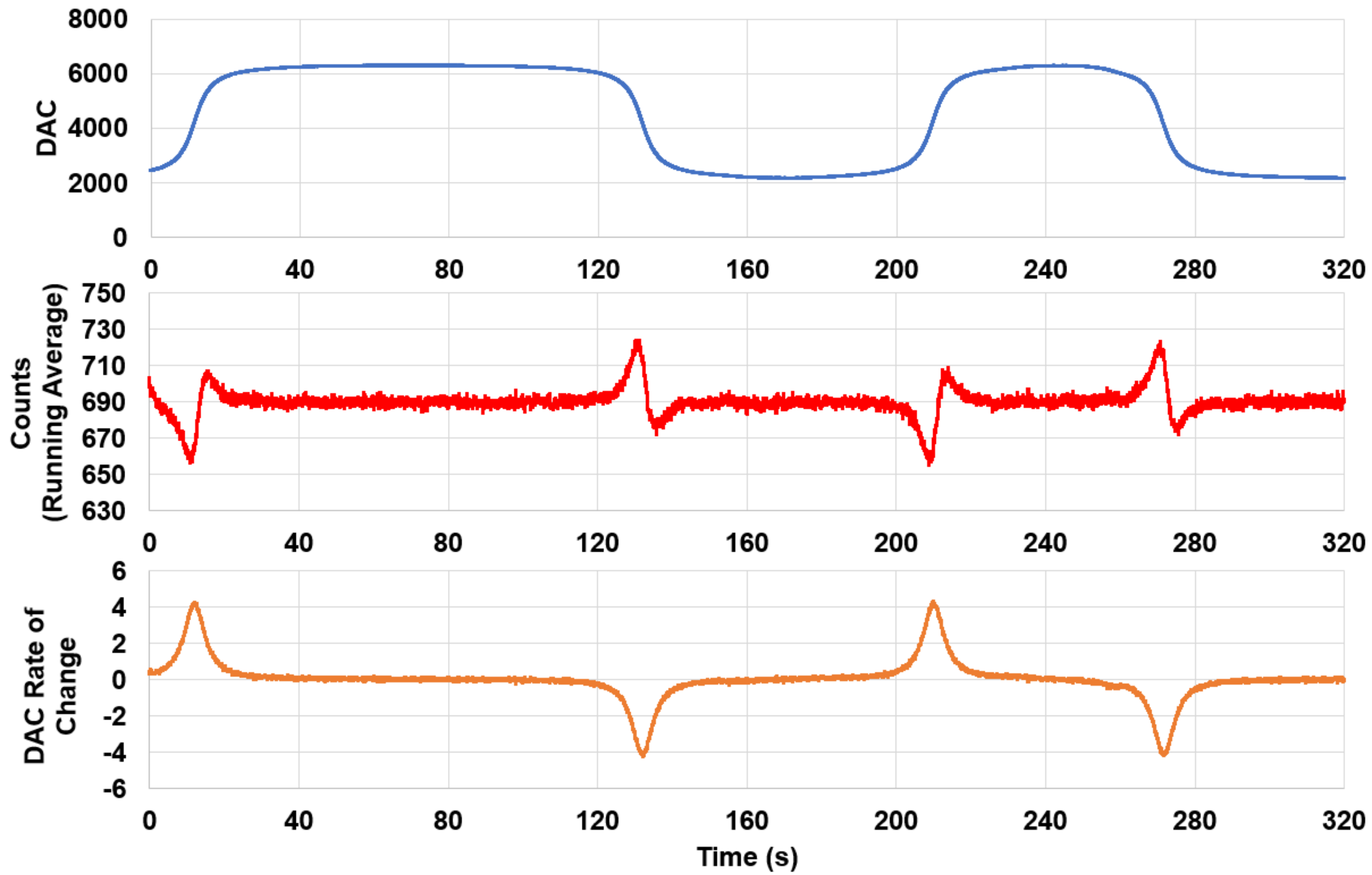


- **PLL uses feedback to control a voltage controlled oscillator (VCO) frequency to null the residual error**
- **Design trades and challenges:**
  - **Loop bandwidth: must be slower than inverse round trip time**
  - **Long time delays can create loop instabilities**
  - **Signal to noise ratio**

Analysis indicates that type-3 loop is needed for dual uplink scenario

F. Gardner, Phaselock Techniques, Wiley, 2005
S. Golestan, et al., IEEE Trans. Power Elec., vol. 28, Nov. 2013

Type-3 Control Loop: Tracking over extended ranges and rate



- **Type-3 control loop tracks the frequency and frequency rate of change to maintain synchronization with a primary source whose frequency is ramping**
- **Control approach compatible with the space-to-ground delay**
- **Testing over modest ranges**
  - **~16 ppb frequency range**
  - **~1.5 ppb/s peak rate of change**
  - **~0.3 ppb/s^2 curvature**

Demonstrated type-3 loop operation appropriate for space-to-ground synchronization; next step was to extend Doppler range and rate capability

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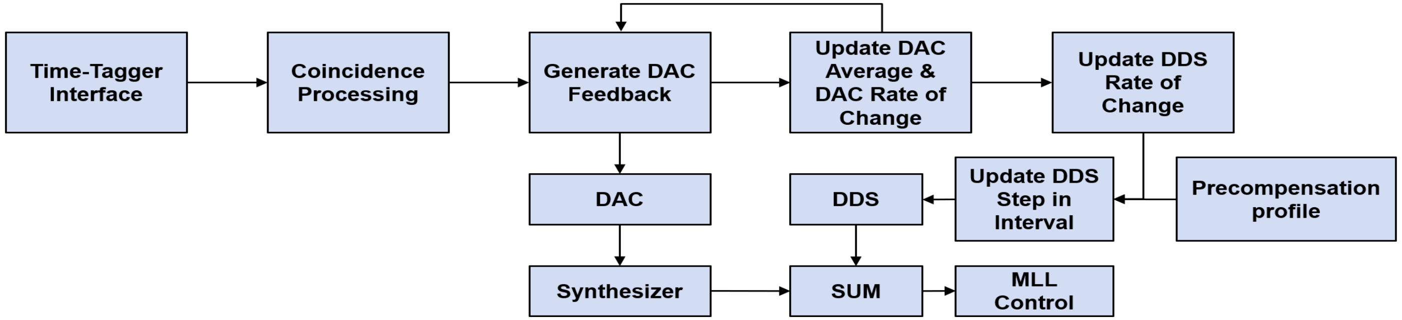
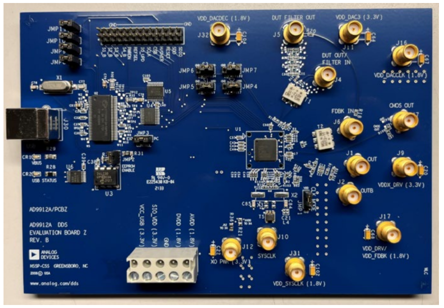
Testbed Configuration: DAC Relaxation for Extended Range Operation

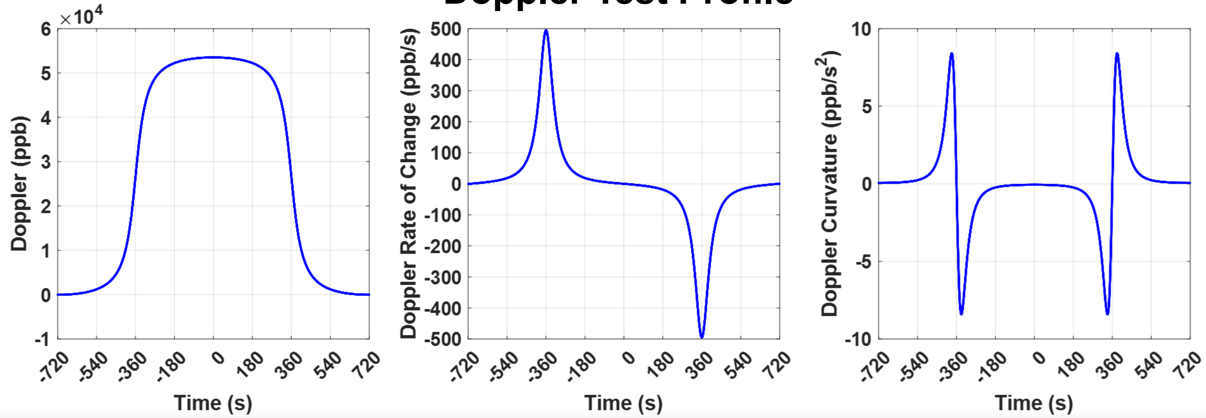
Inner/Outer Relaxation Control Architecture



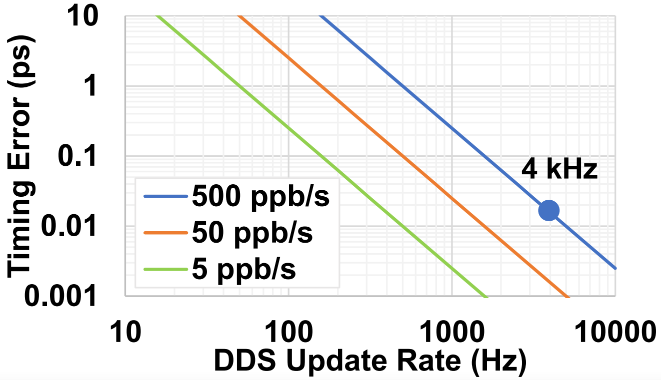
AD9912 Direct Digital Synthesis (DDS) 48-bit control, used at 4 kHz update rate



Doppler Test Profile



DDS Timing Error vs. Update Interval

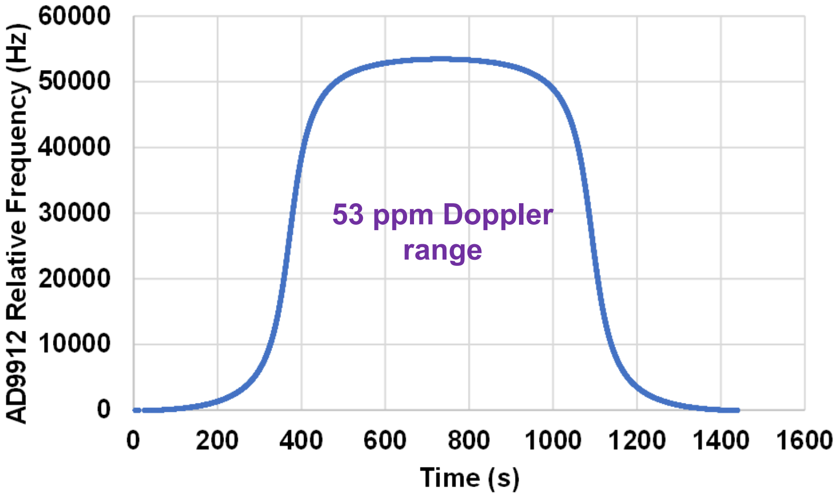


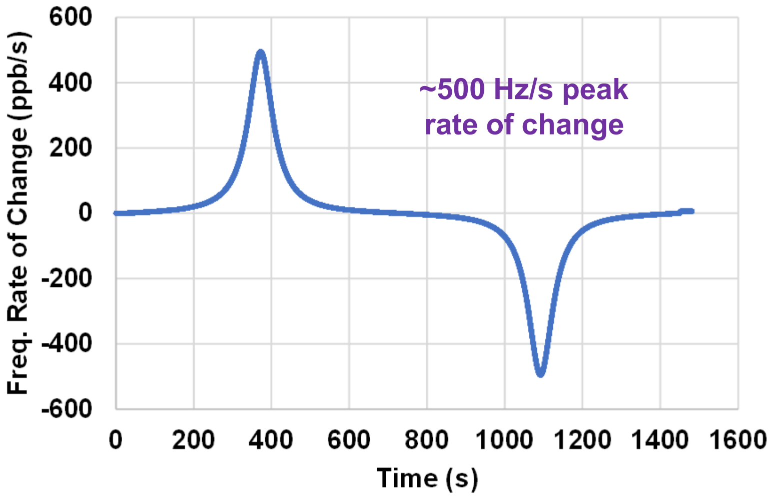
Testbed upgraded to relax DAC by observing DAC rate of change and counter-tuning DDS source

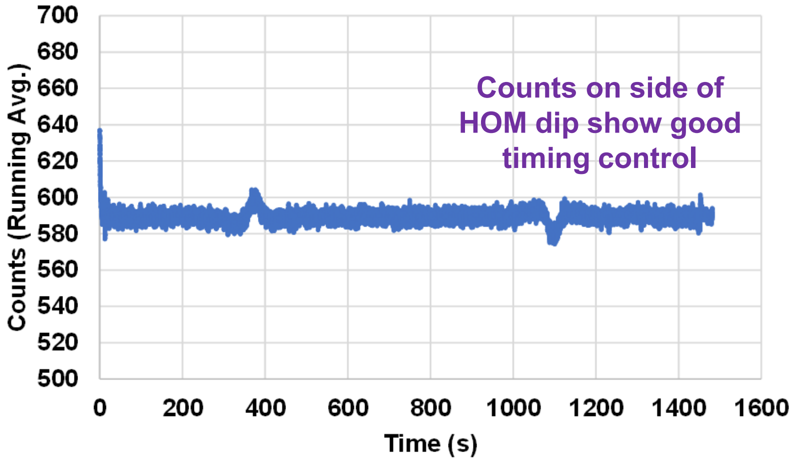
Results: Precision Tracking Over Wide Doppler Range

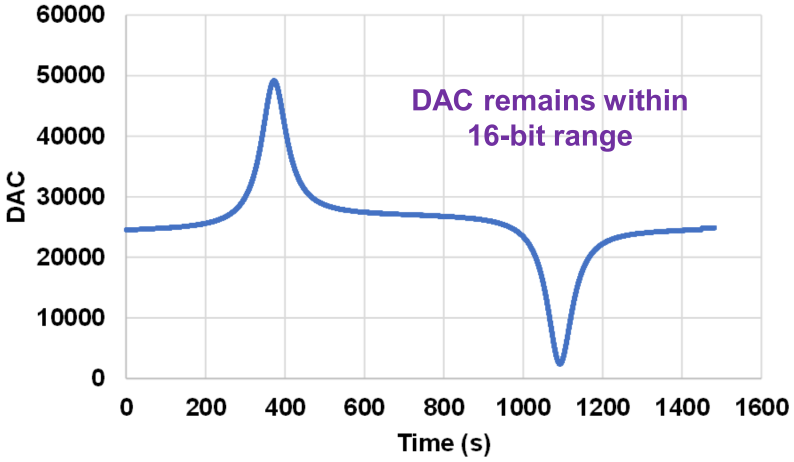
- **Tested over large Doppler**
  - 53 ppm
  - 500 ppb/s
  - 8.4 ppb/s^2
- **<0.25 ps averaged relative timing variation**
- **Outer relaxation control loop maintains DAC within its 16-bit range (<400 Hz range)**

Measurements show excellent performance over large Doppler range & rate









Summary

- Robust synchronization is critical for enabling emerging high-rate long-distance quantum networking
- Dual-uplink and uplink-downlink architectures may enable near term entanglement distribution demonstrations using available lower-SWaP methods
- HOM-based synchronization control method can achieve precision synchronization for wideband situation
- Laboratory testbed provides thorough test capability
- Recent results show precision tracking over realistic LEO Doppler link scenarios